

The Causton Reference  
Cited in Protest Against  
Following Application:

Application No: 10/697,344  
Publication No. 2004/0115084  
Filing Date: October 30, 2003  
For: Method of Producing Powder Metal Parts

Confirmation No. 7505  
Group Art Unit: 1742  
Examiner: Daniel Jenkins



**SILICON CONTAINING HIGH PERFORMANCE ALLOYS –  
MACHINABILITY AND MECHANICAL PROPERTIES**

**Michael C. Baran and Robert J. Causton  
Hoeganaes Corporation, Cinnaminson, NJ**

**John F. Sweet  
FMS Corporation, Minneapolis, MN**

**RECEIVED  
OCT 07 2004  
TC 1700**

**ABSTRACT**

With the introduction of several silicon-containing materials, the potential for replacing ductile and malleable cast irons with P/M alloys has never been greater. These materials exhibit extremely competitive property combinations when conventionally compacted and sintered at 1260 °C (2300 °F). However, additional opportunities exist if advanced densification processes such as double press / double sinter or warm compaction are employed. This paper investigates several important manufacturing processes including advanced densification techniques, vacuum sintering, and machinability.

**INTRODUCTION**

Several silicon-containing materials were recently introduced to compete with malleable and ductile cast irons. These materials are designated as Ancorloy® MDA, Ancorloy MDB, and Ancorloy MDC. Additional grades in the same family are currently being investigated. While previous work on these materials [1-4] has largely focused on conventional single press / single sinter (SP / SS) processing, the investigation of advanced densification processes was warranted.

As an avenue to further improve these superior products, this work investigates double press / double sinter (DP / DS) processing. Vacuum sintering is also examined for the same purpose. Relative machinability comparisons are made between the materials studied and other widely used P/M compositions.

**BACKGROUND**

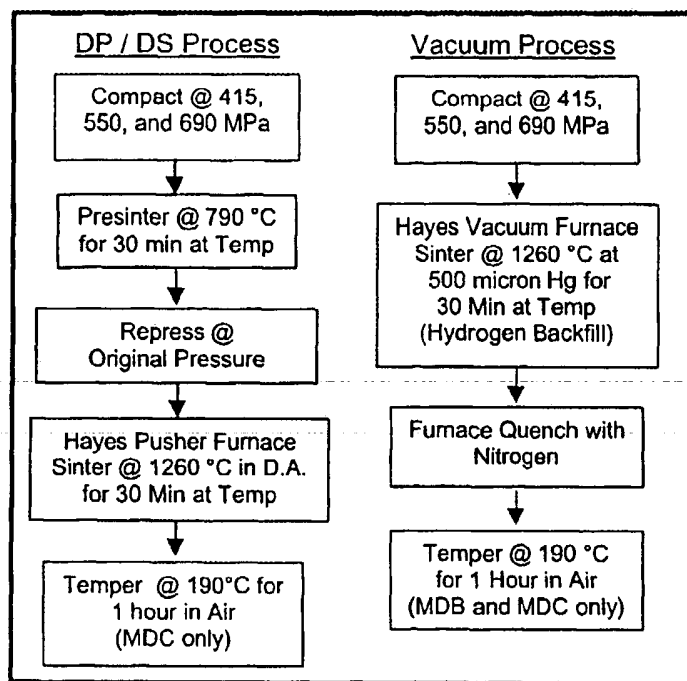
In addition to its relatively low cost and tendency to increase hardenability, silicon can accelerate sintering in hybrid alloys and substantially impact mechanical properties [5]. However, despite the inherent metallurgical advantages of silicon, its use in P/M has been largely unsuccessful in the past. The difficulties associated with conventional methods of silicon addition are numerous. For example, the addition of ferrosilicon almost invariably leads to a high degree of shrinkage and distortion in a sintered P/M compact. Silicon oxide formation during sintering frequently results in an undesirable decline in static and dynamic mechanical

properties. Furthermore, silicon oxide pickup during atomization and/or annealing can lead to lower compressibility and diminished mechanical performance.

Through advancements in atomizing, annealing, and binder-treatment technology, new silicon-bearing materials have been developed to provide exceptional property combinations without large quantities of admixed additions such as nickel, copper, etc. Production experience has indicated that these materials exhibit higher mechanical properties than conventional diffusion-alloyed materials without the additional production costs associated with diffusion alloying.

#### EXPERIMENTAL PROCEDURE

The core materials investigated in this work were Ancorloy MDA, Ancorloy MDB, and Ancorloy MDC, hereafter referred to as MDA, MDB, and MDC. Two processing routes were studied. These included (1) DP / DS processing and (2) conventional single pressing coupled with vacuum sintering. The process flows are presented in Figure 1.



**Figure 1:** Process Flows Utilized in the Study of MDA, MDB, and MDC Materials

Tensile tests were conducted on standard dog-bone tensile specimens. Tensile testing was performed on a 267 kN Tinius Olsen universal testing machine at a crosshead speed of 0.635 millimeters/minute. Elongation values were determined by utilizing an extensometer with a range of 0 to 20%. The extensometer was left on until failure. Apparent hardness measurements were performed on the surface of the specimens using a Rockwell hardness tester. All measurements were conducted on the Rockwell B or C scale (HRB or HRC). Transverse rupture strength and dimensional change from die size were measured according to ASTM B 528 and B 610. Impact energies were determined according to ASTM E 23.

## RESULTS AND DISCUSSIONS

### Powder Properties and Chemistries

The powder properties of interest were apparent density, flow, and chemical composition. These properties are presented in Table I. As can be seen, the flows and apparent densities of MDA, MDB and MDC do not represent a significant departure from similar "high performance" materials.

Table I: Chemical Compositions, Apparent Density, and Hall Flow for Material Grades Tested

Grade	AD (g/cm <sup>3</sup> )	Flow (s/50g)	Fe (w/o)	Si (w/o)	Cr (w/o)	Mn (w/o)	Ni (w/o)	Mo (w/o)	Gr (w/o)
MDA	3.12	30	Bal.	0.7	0.03	0.16	0.05	0.03	0.9
MDB	3.19	28	Bal.	0.7	0.03	0.13	2.0	0.85	0.6
MDC	3.25	28	Bal.	0.7	0.03	0.13	4.0	0.85	0.6

### DP / DS Processing

In the pursuit of higher performance applications, DP / DS processing was employed in an effort to attain sintered densities of 7.30 g/cm<sup>3</sup> or greater. The final sintered densities of the materials are shown in Figure 2, while the key properties measured during this work are listed in Table II.

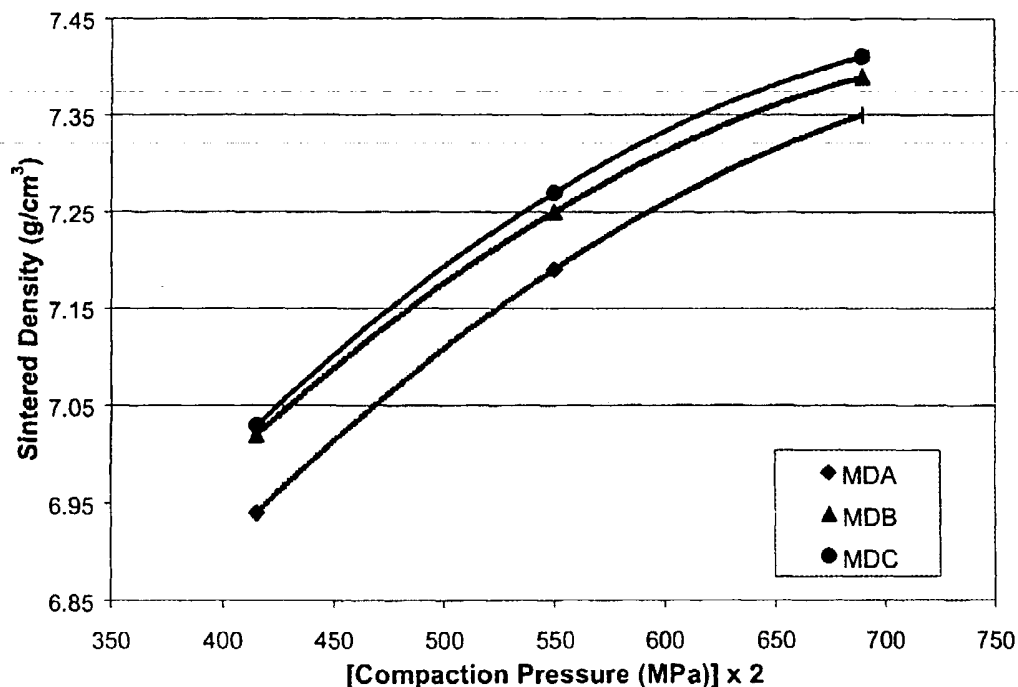


Figure 2: Sintered Density Achieved By DP / DS Processing of MDA, MDB, and MDC Materials (Compaction Pressures Were Identical for Initial Compaction and Repressing Steps)

**Table II: Mechanical Properties of DP/DS Processed MDA, MDB, and MDC Produced by Conventional High Temperature Sintering**

Material	Comp Press. MPa (ksi)	TRS MPa (10 <sup>3</sup> psi)	UTS MPa (10 <sup>3</sup> psi)	YS MPa (10 <sup>3</sup> psi)	Elong (%)	App Hard (HRB/C)	Impact Energy Joules (ft.lbf)
MDA	415 / 415 (30 / 30)	1100 (160)	630 (91)	400 (58)	3.6	77 HRB	--
	550 / 550 (40 / 40)	1340 (194)	680 (99)	400 (58)	4.3	87 HRB	--
	690 / 690 (50 / 50)	1490 (216)	770 (111)	435 (63)	5.4	93 HRB	--
MDB	415 / 415 (30 / 30)	1530 (222)	740 (107)	515 (75)	2.0	89 HRB	--
	550 / 550 (40 / 40)	1695 (243)	850 (123)	535 (78)	2.8	89 HRB	--
	690 / 690 (50 / 50)	1945 (282)	895 (130)	580 (84)	3.5	97 HRB	--
MDC*	415 / 415 (30 / 30)	1990 (289)	1090 (158)	765 (111)	2.2	32 HRC	23 (17)
	550 / 550 (40 / 40)	2365 (343)	1280 (186)	855 (124)	2.6	38 HRC	39 (29)
	690 / 690 (50 / 50)	2655 (385)	1350 (196)	855 (124)	3.0	38 HRC	46 (34)

\*Tempered @ 190 °C for 1 Hour in Air

As seen in iron castings, the materials in this study exhibited a range of strength, ductility, and hardness values. However, unlike iron casting, the studied materials retained a great deal of ductility, despite "high" strengths and hardness. For example, material MDC exhibited tensile strengths greater than or equal to a heat-treated FLN4-4405, while it achieved ductility values comparable to or better than an as-sintered FLN4-4405. Despite the standard furnace cooling employed, apparent hardness values achieved by MDC were found to rival many sinter-hardening compositions employed in the P/M industry.

#### Vacuum Sintering

In an effort to further explore the production processes utilized in the P/M industry, two vacuum sintering trials were conducted at FMS corporation. The first trial focused on tensile and TRS specimens, while the second explored impact properties. Although as-sintered and tempered data was collected for each material, only data from the optimum processing condition was compiled for presentation. While MDA did not benefit from tempering, the mechanical properties of both MDB and MDC properties vastly improved upon tempering. The measured properties of all materials are shown in Table III, while the sintered / tempered densities at which the properties were achieved are shown in Figure 3.

When compared to materials produced by conventional high temperature sintering, a significant increase in yield strength was noted in the vacuum sintered materials [1,2]. For example, while conventional high temperature sintering of these materials was able to produce specimens with yields as high as 830 MPa (120,000 psi), specimens in this study were capable of achieving yield strengths over 1150 MPa (165,000 psi). Not surprisingly, this increase in yield strength was coupled with a moderate reduction in ductility.

Table III: Mechanical Properties of Vacuum Sintered MDA, MDB, and MDC

Material	Comp Press, MPa (10 <sup>3</sup> psi)	TRS, MPa (10 <sup>3</sup> psi)	UTS, MPa (10 <sup>3</sup> psi)	YS, MPa (10 <sup>3</sup> psi)	Elong (%)	App Hard (HRB/C)	Impact Energy, Joules (ft.lbf)
MDA	415 (30)	1000 (145)	580 (84)	460 (67)	1.7	81 HRB	14 (10)
	550 (40)	1225 (178)	675 (98)	525 (76)	2.2	87 HRB	18 (14)
	690 (50)	1310 (190)	740 (107)	570 (83)	2.2	91 HRB	24 (18)
MDB*	415 (30)	N/A	N/A	N/A	N/A	34 HRC	14 (10)
	550 (40)	1450 (294)	1160 (168)	1075 (156)	1.2	38 HRC	18 (14)
	690 (50)	1525 (305)	1205 (175)	1160 (168)	1.1	40 HRC	20 (15)
MDC*	415 (30)	1660 (252)	1000 (145)	885 (128)	1.3	30 HRC	15 (11)
	550 (40)	2050 (296)	1115 (162)	965 (140)	1.4	38 HRC	16 (12)
	690 (50)	2275 (329)	1240 (180)	1020 (148)	1.6	40 HRC	20 (15)

\*Tempered @ 190 °C for 1 Hour in Air

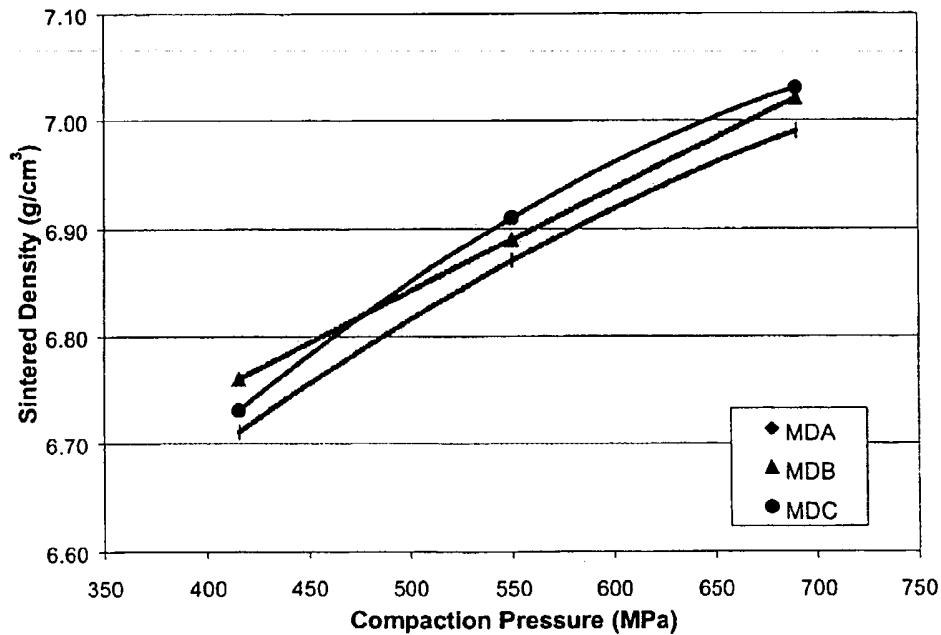


Figure 3: Sintered Densities Achieved By Vacuum Sintering MDA, MDB, and MDC Materials. (Both MDB and MDC Were Tempered @ 190 °C for 1 hour in Air)

Interestingly enough, MDB exhibited equivalent apparent hardness values to MDC, despite 2 w/o less nickel content. This suggested that 4 w/o nickel may not be necessary when the vacuum sintering process is employed.

#### **Machinability**

Preliminary drilling results for sintered MDA, MDB, and MDC provided a frame of reference for the comparison of these materials to traditional P/M compositions. In drilling, the machining behavior of MDA was found to be analogous to a FC-0208 composition. MDB and MDC drilling test results were similar to those exhibited by FLN2-4405 and FLN4-4405, respectively. Production machining experience has confirmed these results. As seen in all high hardness materials, MDB and especially MDC have required some work to optimize machining parameters. The work on machining parameters for green and sintered materials continues.

#### **CONCLUSIONS**

Superior properties were achieved through the implementation of enhanced processing techniques such as DP / DS or vacuum sintering. DP / DS was capable of yielding (1) sintered densities as high as 7.41 g/cm<sup>3</sup>, (2) elongation values as high as 5.4%, and (3) ultimate tensile strengths approaching 1380 MPa (200,000 psi). Vacuum sintering offered (1) yield strengths in excess of 30% greater than seen with conventional high temperature sintering, (2) apparent hardnesses as high as 40 HRC, and (3) opportunities to decrease nickel content by 2 w/o without substantially impacting mechanical properties.

#### **FUTURE WORK**

In anticipation of requests from parts' manufacturers, further study will focus on properties such as rolling contact fatigue (RCF) and rotating bending fatigue (RBF). In addition, mechanical properties will be collected using machined tensile bars instead of dogbone specimens. It is anticipated that the mechanical properties of machined specimens will be superior to those measured on dogbones. Production trials using MDA, MDB, and MDC will also be conducted.

#### **ACKNOWLEDGEMENTS**

The authors would like to thank FMS corporation and Hoeganaes Corporation for their support of this project. In addition, they would like to express their appreciation to George Fillari and Ronald Fitzpatrick of the Hoeganaes Corporation for their contribution in all aspects of specimen preparation, testing, and data collection.

#### **REFERENCES**

1. James, W.B., Causton, R.J., Baran, M.C., and Narasimhan, K.S., "New High Performance P/M Alloy Substitutes for Malleable and Ductile Cast Irons," *Advances in Powder Metallurgy & Particulate Materials*, Metal Powder Industries Federation, Princeton, NJ, 2000.
2. Baran, M.C., Chawla, N., Murphy, T.F., and Narasimhan, K.S., "New High Performance P/M Alloys for Replacing Ductile Cast Irons," *Advances in Powder Metallurgy & Particulate Materials*, Metal Powder Industries Federation, Princeton, NJ, 2000.
3. Baran, M.C., Hanejko, F.G., James, W.B., and Narasimhan, K.S., "Newly Developed P/M Materials to Replace Malleable and Ductile Cast Irons," SAE Technical Paper #2001-01-0404, Society of Automotive Engineers, Detroit, 2001.
4. Baran, M.C., Hanejko, F.G., Causton, R.J., and Narasimhan, K.S., "New Higher Performance Materials," *European Congress and Exposition on Powder Metallurgy*, Munich, 2000.
5. Salak, A., *Ferrous Powder Metallurgy*, Cambridge International Science Publishing, Cambridge, England, 1995, p.235.

# ADVANCES

in Powder Metallurgy &  
Particulate Materials - 2001

*Part 7*

**Materials: Intermetallics,  
Titanium Stainless Steel,  
High Performance Alloys,  
Magnetics**



Compiled by  
William B. Eisen  
Shiz Kassam



# **Advances in Powder Metallurgy & Particulate Materials - 2001**

Proceedings of the 2001 International Conference on Powder Metallurgy & Particulate Materials sponsored by the Metal Powder Industries Federation and APMI International, May 13-17th, New Orleans.

Compiled by

**William B. Eisen**

President

Crucible Research Center

and

**Shiz Kassam**

Director, Advanced Product Engineering

Keystone Powdered Metal Company



**Metal Powder Industries Federation  
APMI International**  
105 College Road East  
Princeton, New Jersey 08540-6692  
Tel: (609) 452-7700 Fax (609) 987-8523



The papers contained in this publication were prepared by the author(s) and reviewed by the session chairmen and submitted for subsequent publication by direct reproduction. The publisher is not responsible for content and/or any deviations from oral presentations from which the papers may have been based.

---

No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior written permission of the publisher.

---

ISBN: 1-878954-82-2

© Copyright 2001  
Metal Powder Industries Federation  
105 College Road East  
Princeton, New Jersey 08540-6692 USA

*All rights reserved  
Produced in the U.S.*

# **Advances in Powder Metallurgy & Particulate Materials — 2001**

## **CONTENTS**

- Part 1 – Design and Modeling of P/M Materials, Components, and Processes, Plus State-of-the-North American P/M Industry**
- Part 2 – Atomization and Powder Production, Particle Size Analysis**
- Part 3 – Lubrication, Green Strength, Spray Forming, Robotics and Consolidation of Powders**
- Part 4 – Powder Injection Molding (Metals and Ceramics)**
- Part 5 – Sintering, Sinter Hardening, De-Lubrication, Dimensional Change Control**
- Part 6 – Secondary Operations: Machining, Surface Treatments**
- Part 7 – Materials: Intermetallics, Titanium Stainless Steel, High Performance Alloys, Magnetics and Consolidation of Powders**
- Part 8 – Refractory Metals, Carbides, Cermets, Ceramics, Foams**
- Part 9 – Composites, Laser Fabrication, Mechanical Alloying, Nanocrystalline Materials, Aluminum**
- Part 10 – Material Properties: Fatigue, Toughness, Creep**
- Part 11 – Process Variation, Testing and Evaluation**
- Part 12 – P/M Issues, Today and Tomorrow**

## **Part 7**

### **Materials: Intermetallics, Titanium Stainless Steel, High Performance Alloys, Magnetics**

Influence of Composition on Thermo-Mechanical Properties of TiNi Shape Memory Alloy Fabricated by Spark-Plasma Sintering Hideki Kyogoku, Toyoaki Tanbo, Masakazu Yokota, Shinichiro Komatsu, Fusahito Yoshida, Tshio Sakuma and Uichi Iwata.....	7-1
P/M High Strength Magnetic Alloys Igor Gabriellov, Christopher Wilson, Tim Weilbaker, Arthur Barrows, Francis Hanejko and George Ellis .....	7-10
Effects of Ordering Transformation and Grain Size on the Magnetic Properties of Fe-Co Alloy Sung Soo Hong, Dae-Gun Kim, Young Do Kim and Kyu Hwan Lee .....	7-22
Iron Powder in Electrical Machines, Possibilities and Limitations Ola Andersson and Alan G. Jack .....	7-26
Effect of Material Insulation and Part Geometry on AC Magnetic Performances of P/M Soft Magnetic Composites L. P. Lefebvre and C. G��linas .....	7-36
Soft Magnetic Powdered Metal Materials for High Frequency Industrial Applications Valentin S. Nemkov, Robert C. Goldstein and Robert T. Ruffini .....	7-51
Effect of Sintering Temperature on NdFeB Permanent Magnetic Materials Mat Husin Saleh, Mazlan Mohammad, Patthi Hussain and Azmi Idris.....	7-63
Development of Low-Coercivity Soft Magnetic Materials from Sponge Iron Powder T.P. Bagchi, Bijoy Sharma, K.C. Sahoo and Animesh Bose .....	7-69
Current Trends of PM Superalloys Discs Production for Gas Turbine Engines Genrikh S. Garibov .....	7-78
Titanium P/M - An Overview F.H. Froes .....	7-84
P/M Titanium Technology for Metal Matrix Composites John H. Moll .....	7-105
Effect of Sintering Atmosphere on Corrosion Resistance and Mechanical Properties of Austenitic Stainless Steels - Part II Prasan K. Samal, Joseph B. Terrell and Erhard Klar .....	7-111

(Continued next page)

An Evaluation of Methods for Improving the Green Properties of P/M Stainless Steels John H. Reinshagen and Richard P. Mason.....	7-121
Effect of Contamination Level and Sintering Temperature On the Corrosion Resistance of P/M 316L Stainless Steel Prasan K. Samal and Joseph B. Terrell .....	7-135
Fine Pitch Powder Metal Gears Using Stainless Steel Alloys Stephen Baker, Mark Foster and Howard Sanderow .....	7-142
Mechanism of Delamination Cracks in High Density Parts S. Ashok, S. SundarSriram, R. KrishnaKumar and Paul Beiss.....	7-156
A New Powder Metal with Mechanical Properties Approaching Low Carbon Steel Thomas G. Fleming and William V. Alcini.....	7-167
High Performance Materials Ancorloy MD Series Suresh O. Shah, Michael C. Baran, Sunil N. Patel and Robert J. Causton.....	7-176
Silicon Containing High Performance Alloys Machinability and Mechanical Properties Michael Baran, Robert J. Causton and John F. Sweet.....	7-185
Comparison of Mechanical Properties for Conventional vs. High Temperature Sintering of FLN2-4405 Low Alloy Steel Howard I. Sanderow.....	7-191
Influence of Sintering Temperature on Properties of Low Alloyed High Strength P/M Materials Ulf Engström.....	7-204
Reentrant Transport Transition in Sintered Superconductors with High Critical Temperature Masahiro Akinaga.....	7-216